

## MULTI-BARRIER PHOTONIC HETEROSTRUCTURES

### CROSS-REFERENCE TO RELATED APPLICATIONS

5           This application claims the benefit of U.S. Provisional Application Serial No. 60/409,334, filed September 9, 2002. This application is related to U.S. Patent Application Serial No. \_\_/\_\_, (Docket - BAT 0089 PA), filed September 9, 2003.

### BACKGROUND OF THE INVENTION

10           The present invention relates generally to the propagation, direction, conditioning and other control of optical signals in optical devices and, more particularly, to the use of photonic bandgap structures in optical devices. Modern telecommunications networks, for example, utilize a variety of optical components to affect control of optical signals and the present  
15           invention presents a scheme for enhancing the performance of such networks by utilizing photonic bandgap structures in the networks. It is noted that reference herein to "bandgap" structures or devices incorporates not only bandgap structures where transmission of a selected wavelength of radiation is inhibited in all directions, but also structures or devices that are spatially selective with reference to the propagation of a particular wavelength of radiation, i.e.,  
20           structures where transmission of a selected wavelength of radiation is inhibited in one direction, or less than all directions.

          For the purposes of defining and describing the present invention, it is noted that the use of the term "optical" throughout the present description and claims is not intended to define a limit to any particular wavelength or portion of the electromagnetic spectrum. Rather, the term  
25           "optical" is defined herein to cover any wavelength of electromagnetic radiation capable of propagating in a waveguide. For example, optical signals in the visible and infrared portions of the electromagnetic spectrum are both capable of propagating in an optical waveguide. A waveguide may comprise any suitable signal propagating structure. Examples of waveguides include, but are not limited to, optical fibers, slab waveguides, ridge waveguides, and thin-films  
30           used, for example, in integrated optical circuits. Complex optical devices such as optical

networks, isolators, circulators, multiplexers, demultiplexers, wavelength lockers, modulators, variable attenuators, dispersion compensators, power monitors, lasers, amplifiers, detectors, routers, switches, interleavers, and combinations thereof, can be configured to incorporate optical waveguides.

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## BRIEF SUMMARY OF THE INVENTION

In accordance with one embodiment of the present invention, an optical heterostructure is provided comprising a matrix and first and second bandgap regions defined in the matrix. The second bandgap region is characterized by a periodic arrangement of inclusions in the matrix.

10 The inclusions have an index of refraction substantially different than the index of refraction of the matrix. The first and second bandgap regions alternate in succession along a primary dimension of optical propagation of the heterostructure device to define a succession including at least one bandgap region of the first type interposed between a pair of bandgap regions of the second type. The first bandgap region defines a first optical bandgap of the optical  
15 heterostructure. The second bandgap region defines a second optical bandgap of the optical heterostructure. The spacing between the band gap regions of the second type created by the interposition of the first band gap region there between is such that the first optical bandgap is centered at a different wavelength than the second optical bandgap and such that a transmission bandwidth is defined between the first and second optical bandgaps. Accordingly, the first and  
20 second bandgap regions each function as optical barriers and the device as a whole comprises a multi-barrier photonic heterostructure.

In accordance with another embodiment of the present invention, an optical heterostructure is provided comprising a matrix and first and second bandgap regions defined in the matrix. The first bandgap region is characterized by a periodic arrangement of first  
25 inclusions in the matrix. The periodic arrangement of the first inclusions in the matrix define a first optical bandgap of the optical heterostructure. The second bandgap region is characterized by a periodic arrangement of second inclusions in the matrix. The periodic arrangement of the second inclusions in the matrix define a second optical bandgap of the optical heterostructure. The first and second inclusions are composed of a material having an index of refraction  
30 substantially different than the index of refraction of the matrix. The first optical bandgap is

centered at a different wavelength than the second optical bandgap.

In accordance with another embodiment of the present invention, an optical heterostructure is provided comprising first and second optical bandgap regions. The first bandgap region comprises an optical medium having a relatively high index of refraction and an optical medium having a relatively low index of refraction. The second bandgap region comprises an optical medium having a relatively high index of refraction and an optical medium having a relatively low index of refraction. The high index optical medium and the low index optical medium of the first bandgap region are arranged in a periodic lattice and define a first optical bandgap. The high index optical medium and the low index optical medium of the second bandgap region are arranged in a periodic lattice and define a second optical bandgap. The first bandgap is centered at a shorter wavelength than the second bandgap.

In accordance with yet another embodiment of the present invention, an optical waveguide is provided comprising a core region and a boundary region having substantially different indices of refraction. The core region defines a primary dimension of optical propagation and is bounded by the boundary region at least along the primary dimension of optical propagation. The core region defines a heterostructure region incorporating an optical heterostructure according to the present invention.

In accordance with yet another embodiment of the present invention, an optical device is provided comprising components configured to function as one of an optical isolator, circulator, multiplexer, demultiplexer, wavelength locker, modulator, variable attenuator, dispersion compensator, power monitor, laser, amplifier, detector, router, switch, interleaver, and combinations thereof, wherein the optical device employs at least one optical heterostructure according to the present invention.

In accordance with yet another embodiment of the present invention, a method of fabricating an optical heterostructure is provided comprising: (i) defining a periodic arrangement of first inclusions; (ii) defining a periodic arrangement of second inclusions; and (iii) forming the periodic arrangement of first and second inclusions in a matrix so as to define first and second bandgap regions in the matrix. The first and second inclusions are composed of a material having an index of refraction substantially different than an index of refraction of the matrix. The first and second bandgap regions define first and second optical bandgaps of the optical

heterostructure. The first optical bandgap is centered at a different wavelength than the second optical bandgap.

5                    **BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS**

The following detailed description of specific embodiments of the present invention can be best understood when read in conjunction with the following drawings, where like structure is indicated with like reference numerals and in which:

10                  Fig. 1 is an illustration of an optical heterostructure according to one embodiment of the present invention;

Fig. 2 is an illustration of an optical waveguide incorporating an optical heterostructure according to one embodiment of the present invention;

15                  Fig. 3 is an illustration of an optical heterostructure according to another embodiment of the present invention; and

Fig. 4 is a representation of the manner in which a multi-barrier photonic heterostructure device according to the present invention operates to generate a well-defined, narrow bandwidth optical signal from a broadband light source.

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## DETAILED DESCRIPTION

Referring to Fig. 1, an optical heterostructure 10 according to the present invention is illustrated. The optical heterostructure comprises a matrix 20 and first and second sets of bandgap regions **A**, **B** defined therein. The first set of bandgap regions **A** is characterized by a periodic arrangement of first inclusions 22 in the matrix 20. The periodic arrangement of the first inclusions 22 in the matrix 20 defines a first optical bandgap of the optical heterostructure 10. The second set of bandgap regions **B** is characterized by a periodic arrangement of second inclusions 24 in the matrix 20. The periodic arrangement of the second inclusions 24 in the matrix 20 defines a second optical bandgap of the optical heterostructure 10.

For the purposes of defining and describing the present invention, it is noted that the term “heterostructure” is merely intended to denote a structure, object, region, or other type of identifiable matter that includes two or more types of identifiable components. For example, the optical heterostructure 10 illustrated in Fig. 1 comprises at least three different identifiable components - the matrix 20, the first inclusions 22, and the second inclusions 24.

The respective characteristics of the optical bandgaps will vary depending upon the requirements of the particular context in which a device according to the present invention is to be utilized. The first optical bandgap is typically centered at a different wavelength than the second optical bandgap and the bandgaps may define different optical widths. For example, and not by way of limitation, referring to Fig. 4, where a narrow band optical signal is to be generated from a broadband or multi-component light source **O** of a wavelength centered around 1.5 $\mu$ m, the second set of bandgap regions **B** may be characterized by a relatively wide band gap centered near 1.5 $\mu$ m and the first set of bandgap regions **A** may be characterized by a more narrow band gap centered at a shorter wavelength of about 1.45 $\mu$ m. Of course, a wide variety of bandgap characteristics will be suitable for various embodiments of the present invention.

Regarding the specific design considerations affecting the band gap characteristics, it is initially noted that the first and second inclusions 22, 24 have an index of refraction substantially different from the index of refraction of the matrix 20. The matrix 20 may have a relatively high index of refraction while the first and second inclusions 22, 24 have a relatively low index of refraction; or, the matrix 20 may have a relatively low index of refraction while the first and second inclusions have a relatively high index of refraction. For the purposes of describing and

defining the present invention, it is noted that indices of refraction that are substantially different or substantially high versus low, define values different enough to establish a waveguide structure permitting efficient propagation of an optical signal  $\lambda$ . For example, in applications where optical heterostructures of the present invention are to be compatible with silica-based waveguides, it is contemplated that suitable indices of refraction of the material forming the first and second inclusions will range from about 1.0 to about 1.5, assuming lower index inclusions in a higher index medium, or from about 1.5 to about 3.5, assuming higher index inclusions in a lower index medium.

Typically, the first and second inclusions 22, 24 are made of the same material and have substantially identical indices of refraction. However, it is contemplated that the first and second inclusions 22, 24 may be formed of different materials and may have different indices of refraction. Suitable materials for the first and second inclusions include, but are not limited to, materials selected from air, an inert gas, silica, a polymer, an aqueous material, and combinations thereof. Similarly, suitable materials for the matrix include, but are not limited to, materials selected from air, an inert gas, silica, a polymer, an aqueous material, and combinations thereof.

The wavelength difference in the first and second optical bandgaps may be attributable to one or more of the following factors: (i) a difference in respective geometries of the first and second inclusions; (ii) a difference in respective sizes of the first and second inclusions (as is the case in Fig. 1); (iii) a difference in the respective periodicities of the first and second inclusions; and (iv) a difference in the respective compositions of the first and second inclusions. In Fig. 1, each of the first inclusions 22 approximate a geometrical shape that is substantially the same as a geometrical shape approximated by each of the second inclusions 24 (i.e., a circle in cross section). However, it is contemplated that, the first inclusions 22 may approximate a geometrical shape that is substantially different than the geometrical shape approximated by the second inclusions 24 (e.g., circles -vs- squares). In any event, it is noted that the first and second inclusions may approximate one or more of a variety of geometrical shapes. It is also noted that differences in sizes may be represented by different cross-sectional areas or volumes. Again, by way of illustration and not limitation, suitable inclusion sizes will range from about 0 $\mu$ m to about 0.5 $\mu$ m in radial cross section, for visible or near-infrared frequencies. Suitable inclusion

periodicities may range from a spacing periodicity of between about 0.3 and about 0.6 $\mu$ m, for visible or near-infrared frequencies.

In Fig. 1, the periodicity approximated by the first inclusions 22 is substantially the same as the periodicity approximated by the second inclusions 22. However, it is noted that the periodicity of the first and second inclusions 22, 24 may be varied, particularly where the sizes of the first and second inclusions 22, 24 are the same. A variety of lattice geometries may be utilized according to the present invention to define the respective periodicities of the first and second bandgap regions A, B. For example, suitable lattice geometries include, but are not limited to, square, cubic, hexagonal, tetragonal, etc., and the features within them could be cylinders, squares, rectangles, hexagons, etc.

The present invention may also be conceptualized by describing the first and second bandgap regions A, B as each comprising different respective optical mediums. Specifically, referring to Fig. 1, bandgap region A comprises two optical mediums 20, 22 while bandgap region B comprises two optical mediums 20, 24. One of the optical mediums in each bandgap region has a relatively high index of refraction while the other optical medium in the bandgap region has a relatively low index of refraction. In each of the bandgap regions A, B, the high index optical medium and the low index optical medium are arranged in a periodic lattice and define a unique optical bandgap having a characteristic center wavelength and width.

As is illustrated in Fig. 1, the first and second bandgap regions A, B alternate along a primary dimension of optical propagation of the heterostructure device 10 to define a plurality of first bandgap regions A and a plurality of second bandgap regions B and yield a two-dimensional photonic bandgap structure. Although not illustrated in the Figs., it is contemplated that the first and second bandgap regions A, B may further alternate along a dimension orthogonal to the primary dimension of optical propagation of the heterostructure device to define a three-dimensional photonic bandgap structure. Similarly, although the Figs. illustrate output signals along one primary dimension of the structure, it is contemplated that the device may be configured to generate output signals in a variety of directions, including those parallel to the incident signal, orthogonal to the incident signal, or at any angle relative to the incident signal.

Although the present invention is illustrated with the inclusion of only two different types of bandgap regions A, B, it is noted that the optical heterostructure 10 may further comprise one

or more additional bandgap regions. The additional bandgap regions would be characterized by a periodic arrangement of additional inclusions in the matrix 20 to define one or more additional optical bandgaps in the optical heterostructure 10. Each of the additional optical bandgaps may be centered at a different wavelength than the first and second optical bandgaps. As is noted  
5 above in the case of the dual bandgap structure, the first, second, and additional bandgap regions may alternate along the primary dimension of optical propagation and the orthogonal dimensions of optical propagation.

The matrix 20 is illustrated in Fig. 1 as defining a substantially homogenous composition throughout the optical heterostructure 10. However, it is noted that the matrix 20 may define a  
10 substantially heterogeneous composition throughout the optical heterostructure. For example, the composition of the matrix 20 may vary from bandgap region A, B to the next. It is further noted that a substantially heterogeneous matrix may have an index of refraction that varies spatially throughout the heterostructure 10. Suitable matrix materials include, but are not limited to, materials selected from Si, In, Ga, Al, Sb, As, Ge, P, N, O, BaTiO<sub>3</sub>, lithium niobate, GaAs,  
15 InP, InGaAsP, a semiconductor, a chalcogenide, a polymer, an organic material, and combinations thereof. The matrix 20 may comprise a dopant, e.g., an optically active material like erbium or another rare earth element.

Referring now to Fig. 2, it is noted that the optical heterostructure 10 of the present invention may be employed in any one of a variety of types of optical waveguides 5. A core  
20 region of the optical waveguide 5 defines a primary dimension of optical propagation. The core region is bounded by a boundary region along the primary dimension of optical propagation. The optical heterostructure 10 of the present invention is defined in a heterostructure region of the core.

The core region of the waveguide may have a relatively high index of refraction while the  
25 boundary region has a relatively low index of refraction. The boundary region may comprise air, silicon dioxide, a material characterized by an index of refraction approximating that of air or silicon dioxide, or combinations thereof. It is noted that the boundary region may comprise a combination of spatially distinct regions, e.g., air above the core and silicon dioxide on each side of the core. It is noted that, intermediate layers or regions of material may exist between the core



and the boundary region without departing from the bounded relationship of the core and the boundary regions.

Referring now to Fig. 3, it is contemplated that suitable optical bandgap properties may be achieved by eliminating the one of the sets of periodic inclusions from one of the band gap regions **A**, **B**, e.g., the first inclusions 22, and establishing an appropriate spacing  $L$  between the bandgap regions having the periodic inclusions 24. For example, in the context of a broadband input optical signal centered at a wavelength of about  $1.55\mu\text{m}$ , it is contemplated that suitable values for the spacing  $L$  between the bandgap regions **B** will range from about  $0.5\mu\text{m}$  to about  $5\mu\text{m}$ , and more particularly near about  $1.0\mu\text{m}$ .

In the context of optically functional waveguides, the matrix 20, the inclusions 22, 24, or both, may comprise an optically functional material such that it exhibits a substantial change in refractive index in response to a refractive index control parameter. For example, the optically functional material may comprises a non-linear photonic material, an electrooptic material, a thermo-optic material, a semiconductor, or combinations thereof. The control parameter may comprise the intensity of an optical signal propagating along the primary dimension of optical propagation, the intensity and distribution of an electric field across the heterostructure 10, the temperature of the heterostructure 10, the free carrier concentration in the heterostructure 10 or a portion thereof, or combinations thereof.

It follows that the present invention is also drawn to a method of controlling electromagnetic radiation. An input signal of electromagnetic radiation may be directed to an optical heterostructure 10 according to the present invention and one or more electromagnetic output signals may be collected there from - the characteristics of the output signal being a function of the input signal, the properties of the optical heterostructure 10, and/or a control parameter. The control parameter may be one of the varieties identified above and, as such, defines properties of the optical heterostructure 10, including, for example, the refractive index of a material within the heterostructure 10.

Although the optical waveguide 5 and the optical heterostructure 10 of the present invention are illustrated schematically in Fig. 2 as defining a two-dimensional bandgap structure, it is again noted that an optical waveguide 5 incorporating an optical heterostructure 10 according to the present invention may be presented as a three-dimensional bandgap structure.

Suitable two and three-dimensional optical devices comprise components configured to function as an optical isolator, circulator, multiplexer, demultiplexer, wavelength locker, modulator, variable attenuator, dispersion compensator, power monitor, laser, amplifier, detector, router, switch, interleaver, or combinations thereof. Nothing in this disclosure is intended to limit the utility of the optical heterostructure of the present invention to a particular type of optical device.

An optical heterostructure 10 according to the present invention may be fabricated to have dimensions compatible with a wide variety of optical waveguides. For example, by way of illustration and not limitation, it is contemplated that

The present invention is further directed to a method of fabricating an optical heterostructure 10 according to the present invention. As can be gleaned from the description of the heterostructure 10 of the present invention, according to a suitable fabrication method, a periodic arrangements of first and second inclusions 22, 24 are defined and formed in a matrix 20 to define first and second bandgap regions **A**, **B** in the matrix.

The periodic arrangements of the first and second inclusions 22, 24 may be defined, for example, in an image transfer mask through electron beam lithography. The first and second inclusions may be formed by transferring an image from an image transfer mask to the matrix 20 through, for example, reactive ion etching. The periodic arrangements of the first and second inclusions 22, 24 are formed so as to alternate along the primary and/or orthogonal dimensions of optical propagation of the heterostructure device 10 to define a plurality of first bandgap regions **A** and a plurality of second bandgap regions **B** in a two or three-dimensional bandgap structure. The method may further comprise doping the matrix 20 or the inclusions 22, 24 with an optically active material.

It is noted that terms like “preferably,” “commonly,” “typically,” and “including” are not utilized herein to limit the scope of the claimed invention or to imply that certain features are critical, essential, or even important to the structure or function of the claimed invention. Rather, these terms are merely intended to highlight alternative or additional features that may or may not be utilized in a particular embodiment of the present invention.

For the purposes of describing and defining the present invention it is noted that the term “substantially” is utilized herein to represent the inherent degree of uncertainty that may be attributed to any quantitative comparison, value, measurement, or other representation. The term

“substantially” is also utilized herein to represent the degree by which a quantitative representation may vary from a stated reference without resulting in a change in the basic function of the subject matter at issue.

Having described the invention in detail and by reference to specific embodiments thereof, it will be apparent that modifications and variations are possible without departing from the scope of the invention defined in the appended claims. More specifically, although some aspects of the present invention are identified herein as preferred or particularly advantageous, it is contemplated that the present invention is not necessarily limited to these preferred aspects of the invention.

What is claimed is: